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US 5642162 A US 5376966 A
Patent Abstracts of Japan & JP3010473 (Nikon Corp.): Vol.15, No.121, pp 91. See abstract.

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INT CL^{6} H04N 1/401 5/217
Online Databases: WPI, JAPIO

(54) Abstract Title
Temperature dependent dark current correction in imaging apparatus

(57) In a method of minimising dark current errors associated with digital samples of a light image generated by sampling the sensed response of an array of light sensitive pixel cells 30 which includes interspersed dark pixels, 34, 36 the dark pixels are formed by shielding all light from pre-selected light sensitive pixel cells. The array of light and dark pixels are characterised to determine the variation of dark current of the light and dark pixels with variations in the temperature of the light sensitive pixel cells. The characterisation is required for each type of process used to fabricate the array of pixels. A reference value of dark current is measured for each light and dark pixel of the array of pixel cells at a reference temperature. An image dark current value is sampled from the dark pixels. A dark current ratio is calculated for each dark pixel by dividing the image dark current value of the dark pixel by the reference value of dark current of the dark pixel. The dark current of each light sensitive pixel cell is calculated from the reference value of dark current of the light sensitive pixel cell and the dark current ratios of the dark pixels. The dark current of each light sensitive pixel is then subtracted from the sampled sensed response of each light sensitive pixel.

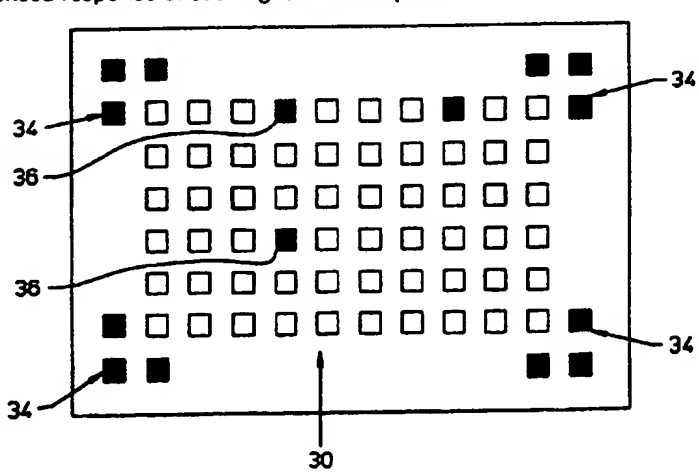

Figure 3

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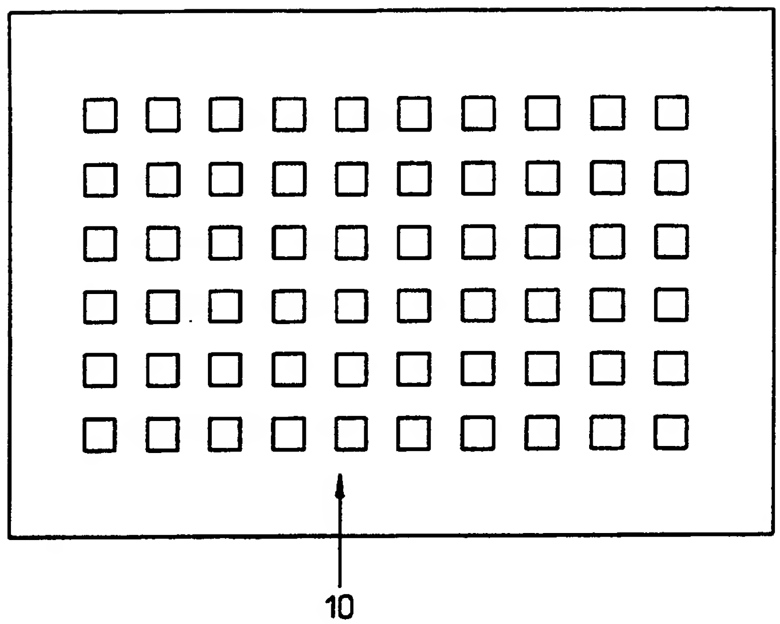

Figure 1 (PRIOR ART)

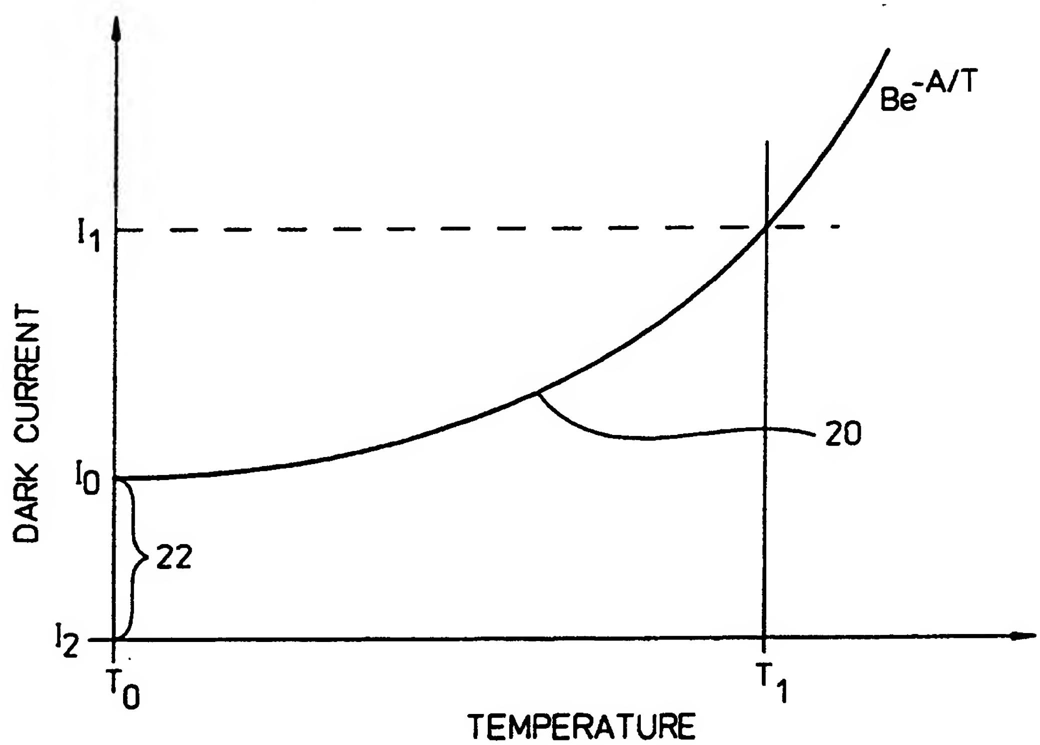

Figure 2

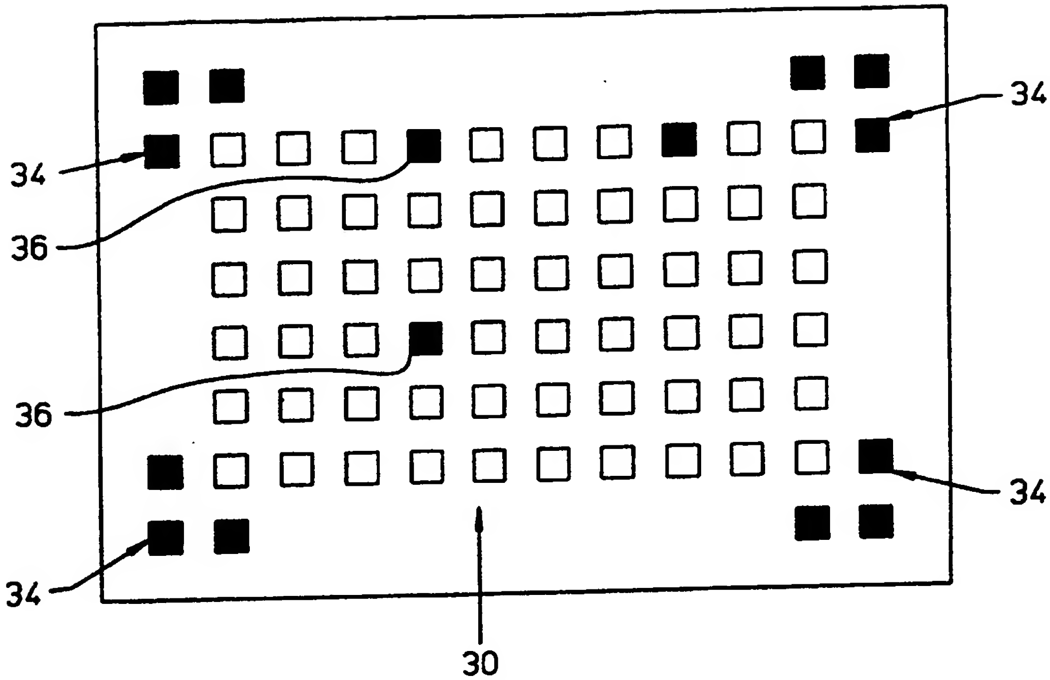

Figure 3

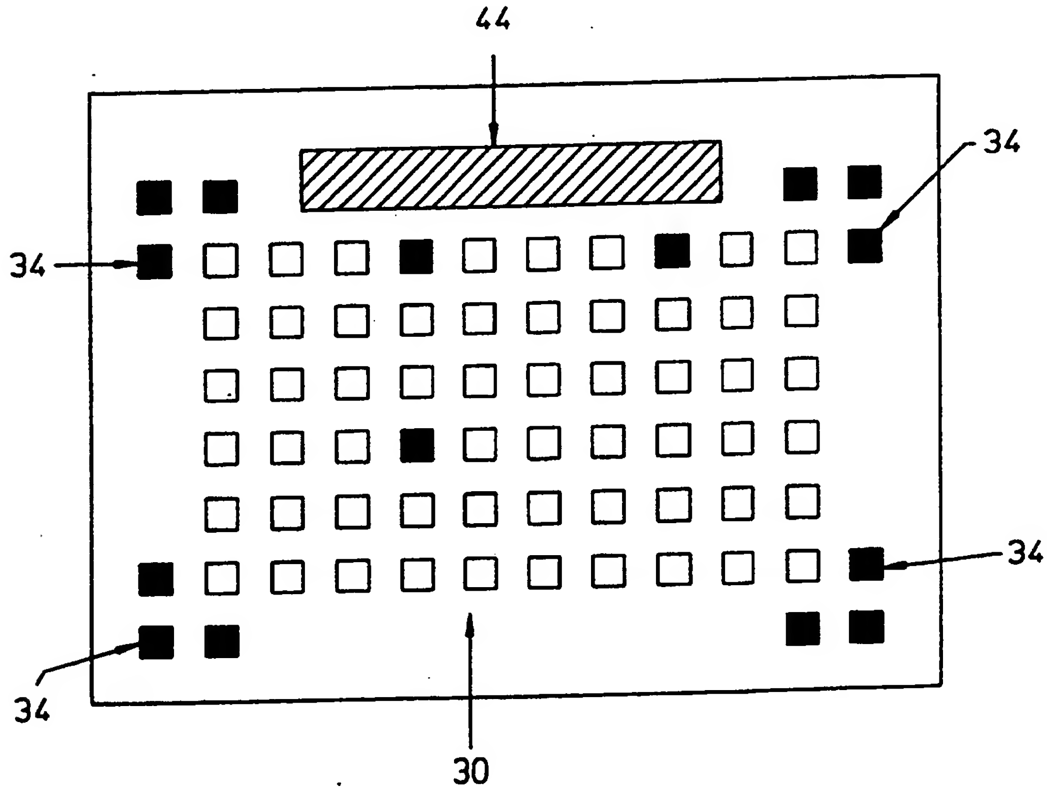

Figure 4

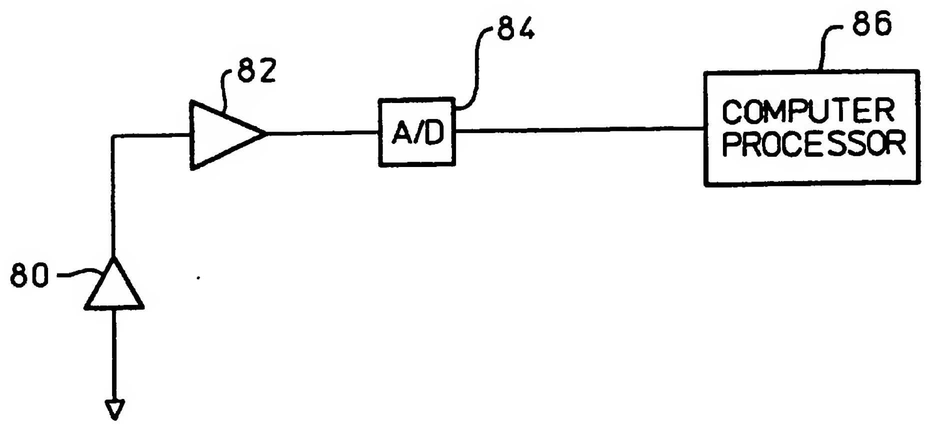

Figure 5

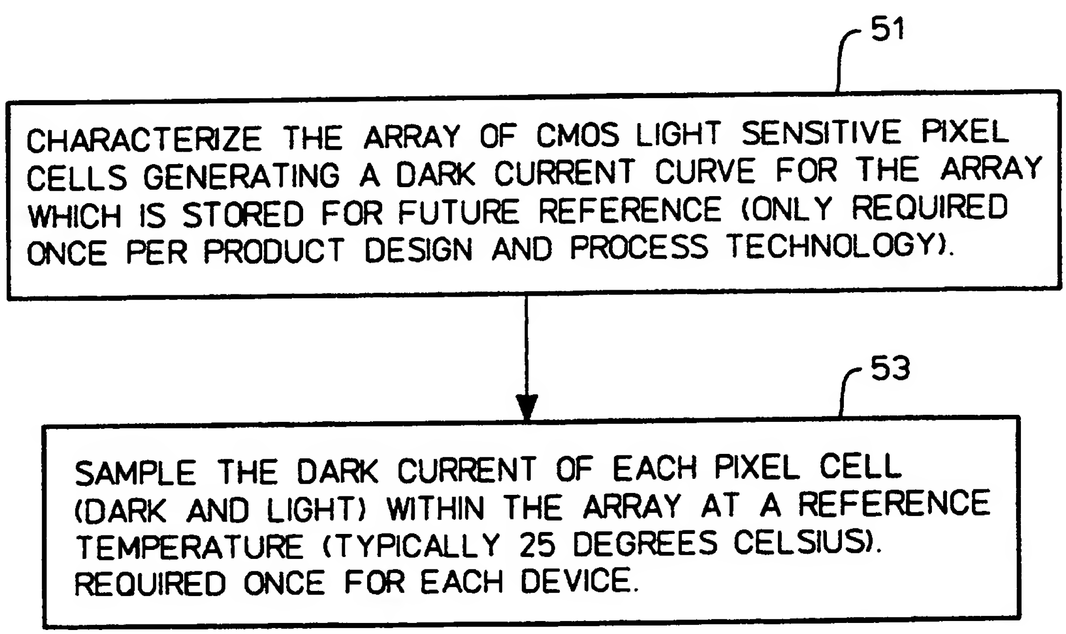

Figure 6

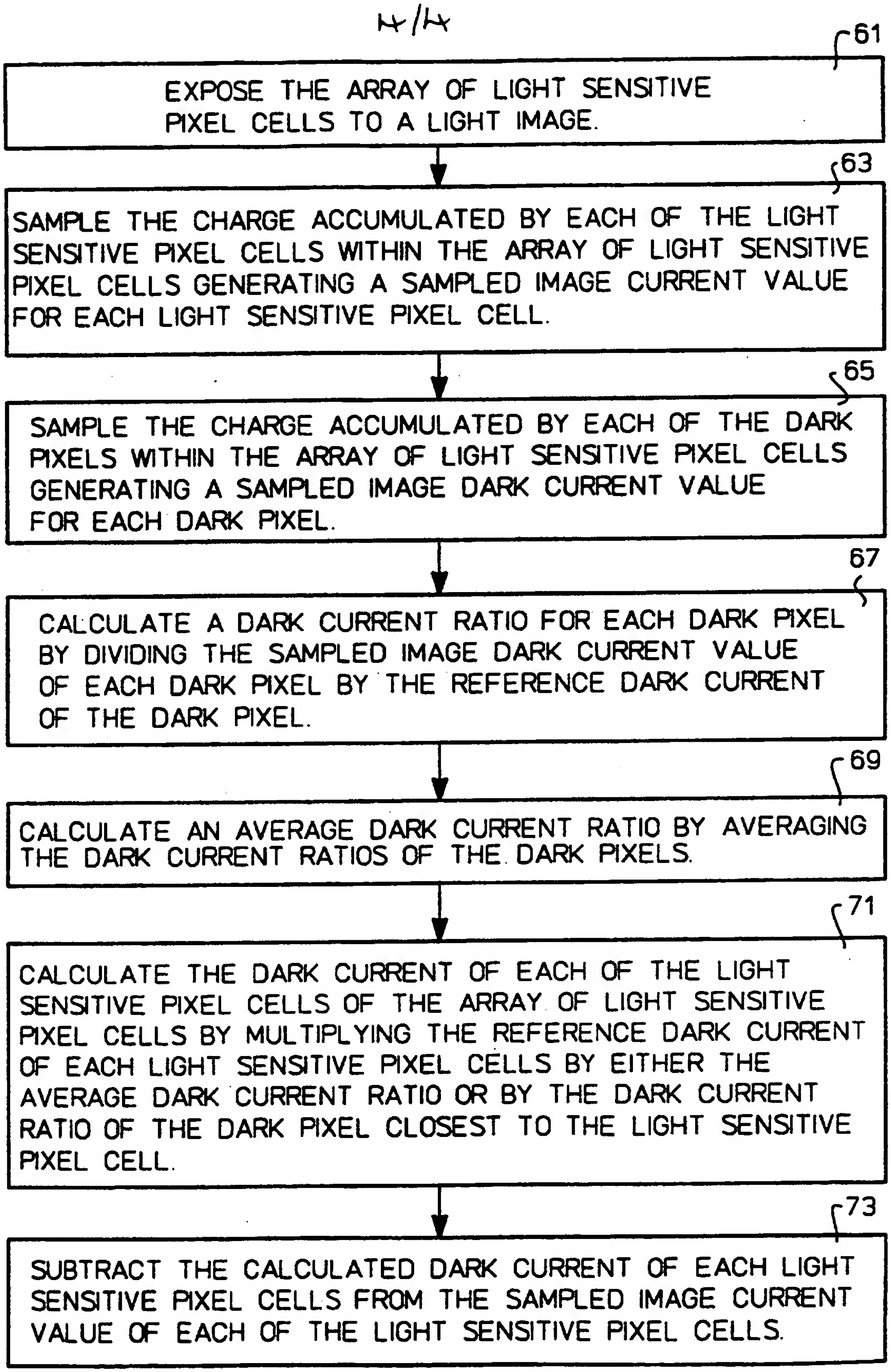
61
EXPOSE THE ARRAY OF LIGHT SENSITIVE PIXEL CELLS TO A LIGHT IMAGE.
63
SAMPLE THE CHARGE ACCUMULATED BY EACH OF THE LIGHT SENSITIVE PIXEL CELLS WITHIN THE ARRAY OF LIGHT SENSITIVE PIXEL CELLS GENERATING A SAMPLED IMAGE CURRENT VALUE FOR EACH LIGHT SENSITIVE PIXEL CELL.
65
SAMPLE THE CHARGE ACCUMULATED BY EACH OF THE DARK PIXELS WITHIN THE ARRAY OF LIGHT SENSITIVE PIXEL CELLS GENERATING A SAMPLED IMAGE DARK CURRENT VALUE FOR EACH DARK PIXEL.
67
CALCULATE A DARK CURRENT RATIO FOR EACH DARK PIXEL BY DIVIDING THE SAMPLED IMAGE DARK CURRENT VALUE OF EACH DARK PIXEL BY THE REFERENCE DARK CURRENT OF THE DARK PIXEL.
69
CALCULATE AN AVERAGE DARK CURRENT RATIO BY AVERAGING THE DARK CURRENT RATIOS OF THE DARK PIXELS.
71
CALCULATE THE DARK CURRENT OF EACH OF THE LIGHT SENSITIVE PIXEL CELLS OF THE ARRAY OF LIGHT SENSITIVE PIXEL CELLS BY MULTIPLYING THE REFERENCE DARK CURRENT OF EACH LIGHT SENSITIVE PIXEL CELLS BY EITHER THE AVERAGE DARK CURRENT RATIO OR BY THE DARK CURRENT RATIO OF THE DARK PIXEL CLOSEST TO THE LIGHT SENSITIVE PIXEL CELL.
73
SUBTRACT THE CALCULATED DARK CURRENT OF EACH LIGHT SENSITIVE PIXEL CELLS FROM THE SAMPLED IMAGE CURRENT VALUE OF EACH OF THE LIGHT SENSITIVE PIXEL CELLS.

Figure 7

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DARK CURRENT CORRECTION IN IMAGING APPARATUS

This invention relates generally to solid state light imaging pixel cells. In particular, it relates to a method of correcting dark current errors in CMOS light imaging sensors.

An electronic image is generally captured by exposing an array of light sensitive pixel cells to a light image. Each light sensitive pixel cell collects charge proportional to the intensity of light received by the light sensitive pixel cell. Electronically sampling the voltage created by the charge collected by each of the light sensitive pixel cells yields an array of samples which represent the image. A light imaging sensor is an array of light sensitive pixel cells.

Figure 1 shows an array 10 of light sensitive pixel cells. The light sensitive pixel cells may be either charge coupled devices (CCDs) or CMOS light sensitive semiconductor imaging devices. Historically, CCDs have been the light sensitive pixel cells typically used in solid state visible light imaging device applications. However, CMOS devices which include photo-gate or photo-diode structures with signal amplification circuits within a light sensitive pixel cell, offer several advantages over CCDs. CMOS devices dissipate less power, can be manufactured less expensively, require lower power supply voltages and are easier to integrate into large scale integrated circuits than CCDs. Additionally, CMOS devices can be manufactured in low cost, high volume application specific integrated circuits (ASICs) CMOS processes. Therefore, ASIC manufacturers can develop light sensitive pixel cells. ASIC manufacturers can further reduce manufacturing costs and provide additional performance benefits as

CMOS technology improves.

CMOS devices, however, accumulate some amount of charge even when not exposed to any light. That is, CMOS devices accumulate charge even when the devices are shielded from all light. The dark charge of a light sensitive pixel cell is the charge accumulated by the light sensitive pixel cell when the light sensitive pixel cell is shielded from all light. The dark current of a light sensitive pixel cell is calculated from the dark charge and time of integration. The dark current varies between light sensitive pixel cells of an array of light sensitive pixel cells. Furthermore, the dark current conducted by each light sensitive pixel cell varies with variations in the temperature of the light sensitive pixel cell. The dependence of the dark current on the temperature of light sensitive pixel cell can generally be characterized by $Be^{-A/T}$, where A is a constant which is dependent on the process technology used to fabricate the light sensitive pixel cell, T is the temperature (Kelvins) of the light sensitive pixel cell, and B is a constant which varies from light sensitive pixel cell to light sensitive pixel cell. The dark current conducted by CMOS devices is roughly 100 times the dark current conducted by CCD sensors.

An electronic image is captured by sampling the charge accumulated by each of the light sensitive pixel cells of an array of light sensitive pixel cells. The amount of charge accumulated by each light sensitive pixel cell is proportional to the intensity of the light received by the light sensitive portion of the light sensitive pixel cell. The dark current of the light sensitive pixel cells reduces the correlation between the value of the charge conducted by the light sensitive pixel cells and the intensity of the light received by the light sensitive pixel cells. The high levels of dark current in CMOS devices increase the noise floor of the output generated by the CMOS devices and reduces the usability of the CMOS devices at low levels of light. If left uncorrected, the dark current will visibly increase the noise associated with an electronic image captured by an array of CMOS light sensitive pixel cells.

The noise effects of the dark current of a light sensitive pixel cell can be minimized by subtracting a sampled value of the dark charge for each pixel cell from a sampled value of the charge accumulated by each pixel cell when exposed to an light image. This can be accomplished by first sampling the response of each of the light sensitive pixel cells of the array of light sensitive pixel cells when the pixel cells are not exposed to light generating a sampled dark current value for each light sensitive pixel cell. The response of each of the light sensitive pixel cells of the array of pixel cells are then sampled when the pixel cells are exposed to a light image generating a sampled light image response for each light sensitive pixel cell. The dark current components of the sampled light image can be minimized by subtracting the sampled dark current value of each pixel cell from the sampled light image response of each light sensitive pixel cell. If the temperature of the array of pixel cells is the same when generating the first samples and when generating the second samples, the dark current errors can be minimized. Sampling the response of each pixel cell of the array of pixel cells two times, however, can require an inconvenient amount of time.

It is desirable to have an apparatus and method which can eliminate the dark current errors associated with an electronically sampled image created by sampling the response of an array of CMOS light sensitive semiconductor devices. Ideally, the apparatus and method would only require the response of the array of CMOS light sensitive pixel cells to be sampled once when capturing an image. Further, the apparatus and method would be operable with an array of light pixel cell fabricated using standard CMOS processes.

The present invention provides an apparatus and method for minimizing the effects of dark current on the output response of an array of CMOS light sensitive pixel cells. The invention only requires the output response of the pixel cells to be sampled a single time. Therefore, the time required to process the output response of the pixel cells is minimized. The invention can be implemented with an array of light sensitive pixel cells formed using standard CMOS fabrication processes.

A first embodiment of the invention includes a method of correcting dark current errors in light image electronic samples of an output response of each light sensitive pixel cell within an array of light sensitive pixel cells. The array of light sensitive pixel cells includes several interspersed dark pixel cells. First, the array of light sensitive pixel cells is exposed to a light image. The charge accumulated by each of the light sensitive pixel cells within the array of light sensitive pixel cells is sampled generating a sampled image current value for each light sensitive pixel cell. The charge accumulated by each of the dark pixel cells within the array of light sensitive pixel cells is sampled generating a sampled image dark current value for each dark pixel cell. A dark current ratio for each dark pixel is calculated from the sampled image dark current of the dark pixel. The dark current of each of the light sensitive pixel cells of the array of light sensitive pixel cells is calculated from the dark current ratios of the dark pixels. Finally, the calculated dark current of each light sensitive pixel cells is subtracted from the sampled image current value of each of the light sensitive pixel cells.

A second embodiment of the invention is similar to the first embodiment. For the second embodiment, the step of calculating a dark current ratio for each dark pixel from the sampled image dark current of the dark pixel includes the following steps. First, a reference dark current for each dark pixel and each light sensitive pixel of the array of imaging pixel cells is measured at a reference temperature. Next, a dark current ratio is

calculated by dividing the sampled image dark current of each dark pixel by the reference dark current of the dark pixel.

A third embodiment of the invention is similar to the second embodiment. The third embodiment further includes estimating the dark current of each of the light sensitive pixel cells of the array of light sensitive pixel cells is by multiplying the reference dark current of each light sensitive pixel cell by an average dark current ratio, or by the dark current ratio of the dark pixel which is closest to the light sensitive pixel cell.

Other aspects and advantages of the present invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the principles of the invention.

Figure 1 shows an array of light sensitive pixel cells.

Figure 2 shows the dark current response of a CMOS light sensitive semiconductor device with variations in the temperature of the device.

Figure 3 shows an array of light sensitive pixel cells including several dark devices or dark pixels.

Figure 4 shows an array of light sensitive pixel cells including several dark devices or dark pixels, and peripheral circuit proximate to the array.

Figure 5 is a circuit schematic which includes the electronic circuitry required to sample the response of a light sensitive pixel cell.

Figure 6 is a flow chart of the characterization steps of the invention which are required before capturing a sampled image with an array of CMOS light sensitive pixel cells and minimizing the dark current errors associated with the captured image.

Figure 7 is a flow chart of the steps of the invention which minimize the dark current errors associated with the sampled response of the captured image.

As shown in the drawings for purposes of illustration, the invention is embodied in an apparatus and method which minimizes dark current errors in a light image response from an array of CMOS light sensitive pixel cells. The invention only requires the response of the array of CMOS device to be sampled a single time for each captured image. The effects of CMOS device dark current on the useful dynamic range of the image response of the CMOS devices is minimized without any changes or modifications in the standard processes used to fabricate the CMOS devices.

Figure 2 shows a dark current curve 20 which represents the dark current conducted by a CMOS light sensitive semiconductor pixel cell as a function of the temperature of the pixel cell. The dark current curve 20 is generated by shielding the light sensitive pixel cells from all light and measuring the charge accumulated by the light sensitive pixel cell as the temperature of the light sensitive pixel cell is varied. There are several features of CMOS light sensitive semiconductor pixel cells associated with the dark current curve 20 that are relevant.

The shape of the dark current curve 20 is dependent on the process used to fabricate the light sensitive semiconductor pixel cell. If two light sensitive pixel cells are formed by the same fabrication process, then the dark current versus temperature curve of the two light sensitive pixel cells will be approximately the same. Generally, all of the light sensitive pixel cells of an array are formed using the same process. Therefore, the shape of the dark current versus temperature curve for all of the light sensitive pixel cells within an array will typically be the same. The dark current for a light sensitive pixel cell varies by approximately a factor of two for every eight degrees Celsius increase in temperature.

The dark current curve 20 of Figure 2 includes an offset I_0 22. The offset I_0 22

is the amount of dark current conducted by a light sensitive pixel cell at a reference temperature T_0. The offset I_0 22 is dependent on the number of defects within each light sensitive pixel cell. The number of defects within a light sensitive pixel cell will vary between different pixel cells within an array of light sensitive pixel cells. Therefore, the offset I_0 22 is typically different for different light sensitive pixel cells within an array of light sensitive pixel cells. The offset I_0 22 can vary by as much as 30% from one light sensitive pixel cell to another within an array of light sensitive pixel cells. The ratio of the dark current of a light sensitive pixel cell at two separate temperatures is generally dependent only on the values of the two temperatures.

The dark current curve 20 is generated for an array of light sensitive pixel cells to confirm that the light sensitive pixel cells do in fact have a dark current dependence on temperature which follows the previously mentioned $Be^{-A/T}$ relationship. The offset I_0 22 is sampled and stored for each light sensitive pixel cell of the array of light sensitive pixel cells at the reference temperature T_0. At any other temperature T_1, the dark current of the dark pixel cells 34, 36 is measured. For each dark pixel 34, 36, a dark current ratio is calculated by dividing the dark current conducted by the dark pixel 34, 36 at temperature T_1 by the dark current conducted by the dark pixel 34, 36 at temperature T_0. The dark current conducted by each light sensitive pixel cells is calculated by multiplying the offset I_0 22 of each light sensitive pixel cell by either the dark current ratio of the dark pixel closest to the light sensitive pixel cell, or an average value of the dark current ratios of all the dark pixels of the array.

Figure 3 shows a first embodiment of the invention. An array of light sensitive pixel cells 30 includes several dark pixels 34, 36. The dark pixels 34, 36 are formed by shielding light sensitive pixel cells from any light. The shielding can be obtained by coating light sensitive pixel cells with an opaque layer to prevent any light from reaching the photo-sensitive areas of the pixel cells.

Several dark pixels 34, 36 are provided to help protect against the existence of any one of the dark pixels being defective. Inner dark pixels 36 are provided within the array of pixel cells 30. The inner dark pixels 36 provide temperature and dark current information where the temperature profile across the array of pixel cells 30 is not uniform. Due to the presence of the inner dark pixels 36, light image information is lost. This lost information can to some extent be recovered by generating sample responses for the locations occupied by the dark pixels by interpolating between the sampled responses of the light sensitive pixel cells proximate to the locations of the inner dark pixels 36.

Figure 4 shows another embodiment of the invention. This embodiment includes peripheral circuits 44 proximate to the light sensitive pixel cells. The proximity of the peripheral circuits 44 increases the temperature of the light sensitive pixel cells located near the peripheral circuits 44. Inner dark pixels 36 located near the peripheral circuits are used to determine the dark current of the light sensitive pixel cells located near the peripheral circuits. As described above, the dark pixels 34, 36 can be used to estimate the dark current of the light sensitive pixel cells.

Figure 5 is a circuit schematic which depicts an embodiment of the electronic circuitry required to sample the response of a light sensitive pixel cell. For this circuit, the light sensitive pixel cell is a photo-diode 80. Charge is accumulated by the photo-diode 80 when the photo-diode 80 is exposed to light. The amount of charge accumulated is proportional to the intensity of the light exposed to the photo-diode 80. An output of the photo diode 80 is coupled to signal amplification and processing circuitry 82. An output of the signal amplification and processing circuitry 82 is sampled by an analog to digital converter 84. The analog to digital converter 84 generates a digital representation of the charge accumulated by the photo-diode 80. A computer processor 86 receives the digital representation of the accumulated charge. The computer processor 86 executes the methods of the invention. The electronic

circuitry required to sample the output of the photo-diode 80 of Figure 6 are known in the art.

Figure 6 is a flow chart of the characterization steps of the invention which are required before capturing a sampled image with an array of CMOS light sensitive pixel cells and minimizing the dark current errors associated with the captured image. A first step 51 includes characterizing the array of CMOS light sensitive pixel cells generating a dark current curve for the array which is stored for future reference. The first step 51 is only required for arrays formed by separate processes. The dark current curve for all arrays formed by a particular process will be approximately the same. A second step 53 includes sampling the dark current conducted by each pixel cell (dark and light) within the array at a reference temperature (typically 25 degrees Celsius). The sampled value of current for each pixel cell is designated as the reference dark current for the pixel cell.

Figure 7 is a flow chart of the steps of the invention which minimize the dark current errors associated with the sampled response of the captured image. The characterization steps of Figure 6 enable the dark current minimization steps of Figure 7. A first step 61 includes exposing the array of light sensitive pixel cells to a light image. A second step 63 includes sampling current conducted by each of the light sensitive pixel cells within the array of light sensitive pixel cells generating a sampled image current value for each light sensitive pixel cell. A third step 65 includes sampling charge accumulated by each of the dark pixels within the array of light sensitive pixel cells generating a sampled image dark current value for each dark pixel. A fourth step 67 includes calculating a dark current ratio for each dark pixel by dividing the sampled image dark current value of each dark pixel by the reference dark current of the dark pixel. A fifth step 69 includes calculating an average dark current ratio by averaging the dark current ratios of the dark pixels. A sixth step 71 includes calculating the dark current of each of the light sensitive pixel cells of the array of light sensitive pixel cells by multiplying the reference dark current of each light sensitive pixel cells by either the

average dark current ratio or by the dark current ratio of the dark pixel closest to the light sensitive pixel cell. Finally, a seventh step 73 includes subtracting the calculated dark current of each light sensitive pixel cells from the sampled image current value of each of the light sensitive pixel cells.

Another embodiment of the invention is a simple camera. The simple camera includes an array of light sensitive pixel cells in which dark pixels are interspersed. Further, the simple camera includes a transferable memory medium in which digital samples from the array of light sensitive pixel cells are stored. The simple camera captures a light image by sampling the light image response of the array of light sensitive pixel cells. The digital samples of the light image are transferred to a computer. The computer includes look up tables which contain dark current information of all of the light and dark pixels within the simple camera. The computer executes the steps shown in Figure 7 to minimize the dark current effects of the light sensitive pixel cells of the simple camera on the digital samples of the captured light image.

Although specific embodiments of the invention have been described and illustrated, the invention is not to be limited to the specific forms or arrangements of parts so described and illustrated. The invention is limited only by the claims.

CLAIMS:

1. A method of correcting dark current errors in light image electronic samples of an output response of each light sensitive pixel cell within an array of light sensitive pixel cells, the array of light sensitive pixel cells including a plurality of interspersed dark pixels, the method comprising:

exposing the array of light sensitive pixel cells to a light image;

sampling charge accumulated by each of the light sensitive pixel cells within the array of light sensitive pixel cells generating a sampled image current value for each light sensitive pixel cell;

sampling charge accumulated by each of the dark pixels within the array of light sensitive pixel cells generating a sampled image dark current value for each dark pixel;

calculating a dark current ratio for each dark pixel from the sampled image dark current of the dark pixel;

calculating the dark current of each of the light sensitive pixel cells of the array of light sensitive pixel cells from the dark current ratios of the dark pixels; and

subtracting the calculated dark current of each light sensitive pixel cells from the sampled image current value of each of the light sensitive pixel cells.

2. The method of correcting dark current errors in light image electronic samples of an output response of each light sensitive pixel cell within an array of light sensitive pixel cells as recited in claim 1, wherein calculating a dark current ratio for each dark pixel comprises:

measuring a reference dark current for each dark pixel of the array of imaging pixel cells at a reference temperature; and

calculating a dark current ratio by dividing the sampled image dark current of each dark pixel by the reference dark current of the dark pixel.

3. The method of correcting dark current errors in light image electronic samples of an output response of each light sensitive pixel cell within an array of light sensitive pixel cells as recited in claim 2, wherein the step of calculating the dark current of each of the light sensitive pixel cells of the array of light sensitive pixel cells from the dark current ratios of the dark pixels comprises:

measuring a reference dark current for each light sensitive pixel cells of the array of light sensitive pixel cells at a reference temperature

determining which dark pixel is closest to each of the light sensitive pixel cells of the array of light sensitive pixel cells; and

calculating the dark current of each of the light sensitive pixel cells of the array of light sensitive pixel cells by multiplying the reference dark current of each light sensitive pixel cell with the dark current ratio of the dark pixel which is closest to the light sensitive pixel cell.

4. The method of correcting dark current errors in light image electronic samples of an output response of each light sensitive pixel cell within an array of light sensitive pixel cells as recited in claim 2, wherein the step of calculating the dark current of each of the light sensitive pixel cells of the array of light sensitive pixel cells from the dark current ratios of the dark pixels comprises:

measuring a reference dark current for each light sensitive pixel cells of the array of light sensitive pixel cells at a reference temperature

calculating an average dark current ratio by averaging the dark current ratio of all of the dark pixels; and

calculating the dark current of each of the light sensitive pixel cells of the array of light sensitive pixel cells by multiplying the reference dark current of each light sensitive pixel cell with the average dark current ratio.

5. A light sensitive imaging apparatus comprising:

an array of light sensitive pixel cells, each light sensitive pixel cell conducting current proportional to the intensity of light received by the light sensitive pixel cell;

a plurality of dark pixel intersperse among the array of light sensitive pixel cells;

means for sampling a charge accumulated by the light sensitive pixel cells and the dark pixels generating a sampled current value for each light sensitive pixel cell and dark pixel;

means for calculating a dark current ratio of each dark pixel from the corresponding sampled current value of the dark pixel and a previously sampled current value of the dark pixel;

means for calculating the dark current of each of the light sensitive pixel cells from the dark current ratios of the dark pixels; and

means for subtracting the dark current of each light sensitive pixel cell from the corresponding sampled current value of each light sensitive pixel cell.

6. A method of dark current correction substantially as herein described with reference to Figs. 2 to 7 of the accompanying drawings.

7. An imaging apparatus substantially as herein described with reference to Figs. 2 to 7 of the accompanying drawings.

The
Patent
Office

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Application No: GB 9816666.3
Claims searched: 1-7

Examiner: Andrew Fearnside
Date of search: 30 October 1998

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.P): H4F FCCE, FCCF, FHHB, FHHE, FHHX

Int Cl (Ed.6): H04N 1/401, 5/217

Other: Online Databases: WPI, JAPIO

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
A	US 5642162 (SONY) Columns 2, 5 & 6. Figure 10(a).	
X	US 5376966 (RICOH) See whole document.	1, 5
X	Patent Abstracts of Japan & JP3010473 (Nikon Corp.): Vol.15, No. 121, pp 91. "Signal correction device for photoelectric converter". See abstract.	1,5

X Document indicating lack of novelty or inventive step
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